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Defining sagittal knee phenotypes via monopedal static anterior tibial translation. Part 2: The assessment-led personalization (ALP) system for indication and correction target planning in slope-reducing osteotomy

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Abstract

Current decision-making for slope-reducing osteotomy (SRO) often relies on isolated posterior tibial slope (PTS) thresholds, potentially misidentifying patients with acquired soft-tissue decompensation or possibly overtreating those with an asymptomatic, inherently hyperlax baseline. Furthermore, rigid point-based scoring systems oversimplify the synergistic biomechanics of the anterior cruciate ligament-deficient knee. Building on the foundational 'Set-Point' theory established in Part 1, this paper introduces the assessment-led personalization (ALP) system. This unified clinical algorithm integrates the normalized percentage of absolute static anterior tibial translation (sATT%) and its side-to-side difference (ΔsATT%) with PTS laterality, generalized hyperlaxity, and injury chronicity. By mathematically calibrating raw translation data to isolate true soft-tissue decompensation from underlying osseous asymmetry, the ALP system provides a proactive, joint-preserving framework to identify high-risk phenotypes likely to fail isolated soft-tissue reconstruction and precisely refines the indications for SRO.

Level of Evidence: Level V.

KEYWORDS
anterior cruciate ligament, personalized surgical decision-making, posterior tibial slope, slope-reducing osteotomy, static anterior tibial translation

For affiliations refer to page 10.

Abbreviations: ACL, anterior cruciate ligament; ACL-R, anterior cruciate ligament reconstruction; ALP, assessment-led personalization; ATT, anterior tibial translation; A + STRA, ACL + slope tracing risk-factor algorithm; GJH, generalized joint hypermobility; HTO, high tibial osteotomy; MCL, medial collateral ligament; MOW-HTO, medial opening wedge high tibial osteotomy; MPD, medial plateau distance; MRI, magnetic resonance imaging; PTS, posterior tibial slope; QR code, quick response code; sATT, static anterior tibial translation; sATT%, normalized percentage static anterior tibial translation; SRO, slope-reducing osteotomy; ΔPTS, side-to-side difference in posterior tibial slope; ΔsATT, side-to-side difference in static anterior tibial translation; ΔsATT%, side-to-side difference in normalized percentage static anterior tibial translation.

INTRODUCTION

As established in Part 1 [13], the sagittal resting position of the knee under monopedal load, measured as static anterior tibial translation (sATT), represents the phenotypic expression of multiple converging risk factors. Osseous anteriorization related to elevated posterior tibial slope (PTS), acquired soft-tissue anteriorization related to injury chronicity and/or meniscal deficiency, and inherent soft-tissue anteriorization related to constitutional hyperlaxity may combine to create biomechanically unfavourable environments in which isolated soft-tissue reconstruction may be at increased risk. To translate this concept into surgical planning, Part 2 introduces the Assessment-Led Personalization (ALP) System: a proposed, standardized algorithm designed to integrate weight-bearing sATT, PTS, side-to-side asymmetry, meniscal status, chronicity and hyperlaxity to support individualized decision-making for slope-reducing osteotomy (SRO).

THE MODIFIERS: THE ROLE OF THE CONTRALATERAL KNEE

PTS and sATT frequently exhibit meaningful side-to-side asymmetry. Tensho et al. demonstrated that clinically relevant PTS asymmetry is more common in anterior cruciate ligament (ACL)-injured patients than in healthy controls, and that the steeper PTS is preferentially located on the non-dominant and injured limb [25]. This suggests that constitutional laterality may locally increase the mechanical burden and lower the threshold for sagittal decompensation. Moreover, Kayaalp et al. demonstrated in a revision anterior cruciate ligament reconstruction (ACL-R) cohort that PTS may increase by >2° over time, particularly in the setting of medial meniscal deficiency [12].

The role of the contralateral knee as a reference remains debated. Some studies comparing ACL-injured patients with healthy controls have suggested increased contralateral laxity [2, 22]. In contrast, in vivo kinematic studies following ACL-R demonstrate stable contralateral ATT over time, with preserved dynamic ATT during level and downhill running preoperatively and up to 2 years post-operatively [3, 24]. These findings support the contralateral knee as a valid internal comparator when interpreted within patient-specific context.

Within the ALP system, laterality should be regarded as a modifier rather than a confounder. Side-to-side differences in PTS and sATT, particularly when the non-dominant limb demonstrates a markedly steeper PTS, may reflect a constitutional risk factor and should be incorporated into risk stratification and surgical planning, including consideration of SRO in selected patients.

THE ALP SYSTEM FOR CLINICAL DECISION-MAKING FOR SLOPE-REDUCING OSTEOTOMY

Phase 1: The standardized acquisition protocol

Objective: Eliminate the 'Nomenclature Trap' by ensuring true loading and mitigating radiographic magnification errors.

1. *Imaging requirement*:
   - *Recommended*: Strict monopedal weight-bearing lateral radiographs at approximately 20° of knee flexion, with sufficient visualization of the proximal tibial axis, preferably including at least 15 cm, to allow reliable assessment of sagittal alignment and PTS [7, 15].
   - *Technique*: The x-ray beam must be centred directly on the knee joint (not the tibial shaft) to ensure precise superimposition of the femoral condyles [9, 15].

2. *Measurement method*:
   - *Reference*: Medial tibial plateau.
   - *Normalization protocol*: To eliminate magnification errors inherent to absolute millimetre measurements, translation should be expressed as a percentage (sATT%) [5]. This is calculated by dividing the absolute ATT distance by the medial plateau distance (MPD), defined as the distance from the most superior aspect anteriorly to the most superior aspect posteriorly of the medial plateau, and multiplying by 100.

Phase 2: The core metrics and calibration

Objective: Gather the quantitative inputs and calibrate for constitutional asymmetry to define the sagittal phenotype.

For both the *Injured (Index)* and *Contralateral (Healthy)* knee, determine the following three variables:

1. *Posterior tibial slope*: Measure the medial PTS on the standardized lateral radiograph using the proximal tibial axis as the reference line [7].
2. *sATT percentage (sATT%)*: Measure the distance of the medial tibial plateau resting anterior to the posterior femoral condyle under monopedal load, expressed as a percentage of the MPD.
3. *Calculate ΔsATT (the raw discriminator)*: Determine the side-to-side asymmetry to isolate pathological decompensation from a constitutional baseline.

- *Formula*: ΔsATT = sATT%{index} − sATT%{contralateral}

- *Establishing the Equivalence Ratio*: While historical literature has well-established thresholds for absolute side-to-side differences in *passive laxity* and dynamic excursion (e.g., 1.3 mm representing physiological asymmetry [8], and ≥3 mm indicating pathological ligamentous incompetence [6]), a standardized metric for evaluating asymmetric resting sagittal position under load has been lacking. To establish ΔsATT as a reliable diagnostic parameter and translate these recognized biomechanical heuristics into a magnification-independent metric, we utilize paired cohort data demonstrating that a 1 mm absolute translation equates to an approximate 2.3% relative translation in the ACL-deficient state [5].
- *Defining the Thresholds (Provisional)*: By formalizing ΔsATT as a core metric and applying this equivalence ratio, a low ΔsATT is defined as falling within this symmetrical physiological range (e.g., ≤3%), typically indicating a benign, constitutional baseline, based on in vivo kinematic data indicating physiological side-to-side asymmetry is minimal (e.g., =1.3 mm) [8]. Conversely, a high ΔsATT (e.g., ≥7%, translated from the ≥3 mm pathological limit [6]) represents a severe pathological sagittal shift. These values serve as the foundational, working thresholds to identify functional decompensation within the ALP system, remaining subject to ongoing prospective clinical validation.

4. *The Asymmetry Calibration: Reverse-Engineering Osseous Laterality*: Because PTS directly drives ATT, a constitutional side-to-side difference in osseous morphology (ΔPTS) will inherently inflate or mask the measured ΔsATT%. To accurately quantify true soft-tissue decompensation, the clinician must first mathematically isolate and subtract the translation caused strictly by bony asymmetry.

- *The PTS Adjustment Factor*: The provisional PTS adjustment factor is derived from clinical monopedal weight-bearing radiographic data suggesting that each 1° increase in PTS is associated with approximately 0.5 mm greater sATT in the ACL-deficient state [4]. Applying the translation equivalence ratio described above, in which 1 mm of absolute translation corresponds to approximately 2.3% relative sATT% [5], this yields an estimated 1.15% relative sATT% per 1° of PTS increase, rounded to approximately 1.2% per degree. This value should be interpreted as a provisional calibration within the ALP system rather than a validated correction factor.
- *The Adjustment Formula*: Because PTS asymmetry may partly explain side-to-side differences in weight-bearing sATT, ΔsATT% should be interpreted together with ΔPTS. Within the ALP system, we propose a provisional calibration in which the measured ΔsATT% is adjusted by approximately 1.2% for each 1° of ΔPTS. Thus, if the index knee has the steeper PTS, ΔsATT% is reduced by this factor to estimate the residual translation not attributable to osseous asymmetry alone; if the index knee has the lower PTS, ΔsATT% is increased accordingly. This adjustment is intended as a conceptual estimate, not as a validated diagnostic threshold, and requires prospective validation.
- *Kinematic Validation*: This adjustment perfectly aligns with established in vivo kinematics. Gale et al. demonstrated that maximum physiological side-to-side translation over the gait cycle is approximately 1.3 mm [8], which conceptually translates to a ~3% sATT% baseline variance. A benign constitutional PTS asymmetry of 2° would generate a 2.3% translation difference (2° × 1.15%), falling within this physiological noise. In contrast, in vivo quasi-static lunge data demonstrate that isolated ACL deficiency induces an additional ~3 mm anterior shift [6] (translating to ~7% sATT%). Once the structural variance (ΔPTS) is reverse-engineered out of the equation, a residual ΔsATT% approaching or exceeding this 7% threshold effectively pierces the physiological envelope, signifying a pathological anteriorization, pending prospective studies to refine these preliminary cut-offs (Figure 1).

Phase 3: The classification logic

Objective: Identify the dominant mechanism driving the sagittal decompensation using the Adjusted ΔsATT%.

Using the calibrated inputs from Phase 2, the clinician categorizes the patient into their specific sagittal phenotype and assesses the cumulative risk profile to determine the indication for SRO (Figure 2, Table 1).

Type 1: Osseous Anteriorization (PTS-Driven)

- *Profile*: High PTS (≥ 12°) + High Adjusted ΔsATT% (e.g. ≥7%).
- *Mechanism*: Bony geometry creates a continuous gravitational vector pushing the tibia forward. The ACL acted as the primary 'brake'; without it, the steep PTS dominates the joint's resting equilibrium.
- *Clinical Pearl*: Active stabilizers (e.g., hamstrings) cannot counteract steep osseous PTS under axial load.
- *SRO Consideration*: SRO may be considered in selected high-risk patients, particularly in the absence of constitutional knee recurvatum.

Type 2: Acquired Soft-Tissue Anteriorization (Decompensation due to Chronicity/Meniscus)

- *Profile*: Borderline/Normal PTS + High Adjusted ΔsATT% (e.g. ≥7) + Chronic Injury (> 12 months) and/or Meniscus Deficiency.
- *Mechanism*: The 'Meniscal Multiplier.' The loss of the posterior meniscal wedge and progressive soft-tissue

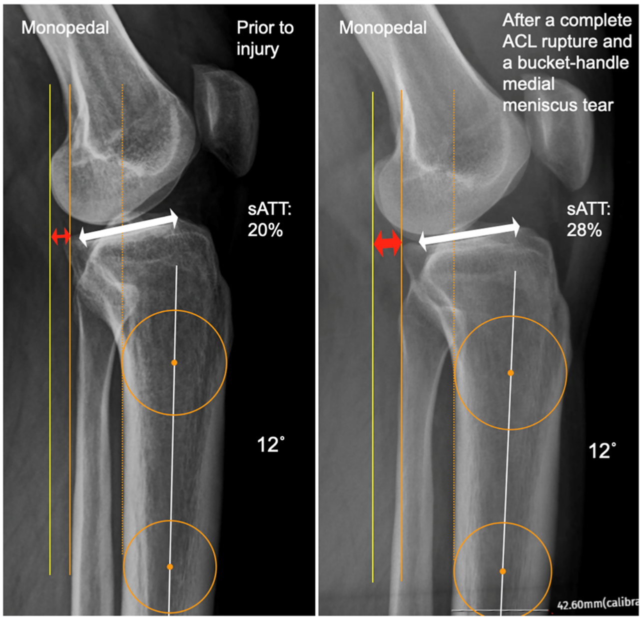

FIGURE 1 Pre- and post-injury monopedal weight-bearing lateral radiographs of the same knee of a patient demonstrating acquired sagittal instability. Monopedal weight-bearing lateral radiographs of the identical knee in a 27-year-old male, captured both prior to injury (left) and acutely (less than two weeks) following an anterior cruciate ligament (ACL) rupture with a concurrent medial meniscus bucket handle tear (right). The pre-injury image (left) establishes the patient's native sagittal set-point under physiologic load, demonstrating a steep posterior tibial slope (PTS) of 12° and an elevated baseline static anterior tibial translation (sATT) of 20%. Notably, the patient presents with a Beighton score of 2 (isolated to bilateral genu recurvatum), providing localized inherent soft-tissue compliance that accommodates the PTS-driven anterior baseline. Following the acute injury (right), the sudden loss of the primary ligamentous restraint, compounded by the immediate loss of the secondary meniscal wedge, unleashes the continuous anterior shear vector. The joint is driven into severe acquired instability, with the sATT surging an absolute 8% to reach 28%. This rare, same-knee comparison provides a stark illustration of how the acute loss of the soft-tissue envelope destabilizes the sagittal equilibrium.

creep create a 'functional PTS increase', mimicking the hostile biomechanics of steep bony geometry.

- *Clinical Pearl*: Time and meniscal loss are the primary drivers of this pathological shift.
- *SRO Consideration*: SRO may be considered on an individualized basis, particularly when the medial meniscus, especially the posterior horn, is irreparable or functionally deficient. Conversely, medial meniscal integrity should not automatically exclude SRO consideration, as PTS reduction may theoretically protect a repaired or vulnerable meniscus in selected high-risk phenotypes.

Type 3: Inherent Soft-Tissue Anteriorization (Hyperlaxity)

- *Profile*: High Absolute sATT% bilaterally + Low Adjusted ΔsATT (e.g. ≤3%).
- *Mechanism*: Generalized ligamentous laxity. The tibia rests in an anterior position because the systemic soft tissues are constitutionally compliant, not because the secondary stabilizers have failed unilaterally.
- *Clinical Pearl*: Symmetric bilateral anteriorization may reflect constitutional laxity rather than unilateral sagittal decompensation. Always evaluate for concurrent genu recurvatum.
- *SRO Consideration*: SRO should be approached cautiously in this phenotype because the anterior sagittal resting position may reflect the patient's constitutional laxity-related baseline rather than unilateral sagittal decompensation. In selected cases, surgical planning may instead emphasize soft-tissue augmentation strategies, such as non-hamstring autografts and/or lateral extra-articular procedures, depending on the overall instability profile [14].

Clinical modifiers and complex presentations in the ALP system

While the three-phase classification logic provides a robust foundational algorithm for evaluating weight-bearing sagittal position, surgical decision-making in the real world rarely exists in isolation. Because clinical evaluations are inherently subjective, the ALP system should be contextualized by considering critical clinical modifiers and recognizing complex multiplanar presentations that can influence the treatment pathway. For instance, although acquired soft-tissue anteriorization typically groups chronicity with meniscal deficiency, SRO may occasionally be indicated in the primary, acute setting [23, 26]. If a patient presents acutely following an ACL rupture with intact menisci but an extreme structural profile (PTS ≥ 14–16°) and a high ΔsATT, this represents a highly hostile biomechanical environment. In such Type 1 phenotypes, isolated soft-tissue reconstruction may fail to protect the intact secondary stabilizers. Provided there is no concurrent genu recurvatum, a primary supratubercle or infratubercle level SRO [16] might be considered to proactively neutralize the gravitational shear vector.

The presence of genu recurvatum itself is a paramount consideration that should be carefully considered before deciding on an SRO. Although current literature frequently cites genu recurvatum ≥10° as a strict contraindication, clinical experience dictates that planned PTS correction can unmask or exacerbate even mild baseline hyperextension (≥ 5°), resulting in a symptomatic iatrogenic deformity. Crucially, the acquired soft-tissue anteriorization and flexion bias inherent to an injured, ACL-deficient knee can biomechanically hide an underlying recurvatum. Therefore, the contralateral, structurally intact knee should be thoughtfully evaluated clinically and radiographically to

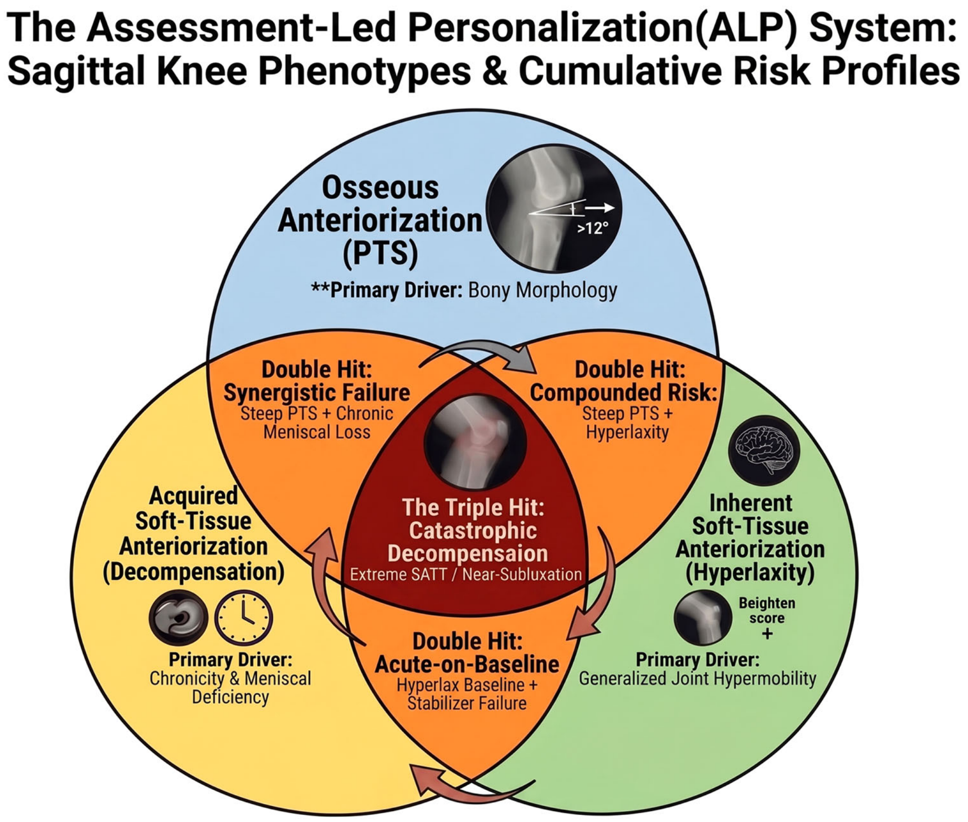

FIGURE 2 The assessment-led personalization (ALP) system: Sagittal knee phenotypes and cumulative risk profiles. This conceptual Venn diagram illustrates the proposed three primary pathomechanisms associated with elevated static anterior tibial translation (sATT) and their potential interactions. The isolated outer circles define the baseline phenotypes: Osseous anteriorization (blue), acquired soft-tissue-based anteriorization (yellow) and inherent soft-tissue-based anteriorization (green). The overlapping regions illustrate how these mechanisms may coexist and contribute to a progressively more complex sagittal risk profile. 'Double Hit' phenotypes (orange zones) represent the convergence of two mechanisms, such as steep posterior tibial slope combined with chronic meniscal deficiency, which may increase the mechanical burden on the central pivot. The central 'Triple Hit' phenotype represents the coexistence of osseous morphology, inherent soft-tissue laxity and acquired soft-tissue deficiency, potentially resulting in marked sagittal decompensation. The overall colour spectrum functions as a clinical heatmap to visualize increasing biomechanical complexity within the proposed ALP framework: Cool colours (green, blue) represent more isolated phenotypes, whereas progressively warmer colours (orange to red) represent increasingly compounded risk profiles that may warrant closer consideration of sagittal-plane correction strategies, including slope-reducing osteotomy (SRO), in selected patients. This visual framework should not be interpreted as an evidence-based treatment guideline. Prospective clinical validation is required to determine how these phenotypes should guide SRO decision-making.

establish the patient's true constitutional extension baseline. Preventive strategies to reduce the risk of post-operative recurvatum may include protected or non-weight-bearing rehabilitation [19, 20], temporary brace immobilization and a carefully individualized graft fixation strategy, including ACL graft fixation at deeper flexion angles in selected cases. However, fixation at deeper knee flexion angles should not be generalized across graft types, as it may be more applicable to less stiff graft constructs and may risk extension loss with stiffer extensor mechanism grafts. Objective clinical studies are needed to support these strategies.

Beyond the sagittal plane, an accompanying coronal deformity should also be considered during surgical planning. If symptomatic coronal malalignment is present, such as relevant varus deformity, an isolated anterior closing-wedge SRO may be insufficient to address the multiplanar deformity. In this context, PTS correction may need to be combined with coronal realignment. A biplanar medial high tibial osteotomy with differential anterior–posterior opening or a combined osteotomy strategy may allow simultaneous correction of coronal alignment and PTS in selected patients. However, the achievable degree of PTS correction is technique-dependent and should be determined by individualized preoperative planning, hinge position, wedge geometry, and intraoperative safety considerations, particularly the risk of hinge fracture. Therefore, rather than applying a fixed correction target, sagittal correction should be planned case by case and interpreted within the broader multiplanar alignment strategy (Figure 3). While the detailed technical

TABLE 1 The assessment-led personalization (ALP) system classification.

ALP classification	Primary drivers	Radiographic profile (monopedal weight-bearing)	Pathomechanical mechanism	SRO indication/clinical pathway
Type 1: Osseous (*PTS-driven*)	Bony morphology (steep PTS) + loss of the ACL 'brake'	PTS: ≥ 12° Adj. ΔsATT: High (≥ 7%)	Gravitational vector: Uncompensated steep osseous geometry drives the tibia forward under axial load.	SRO may be considered in selected high-risk patients
Type 2: Acquired soft-tissue-based (decompensation)	Chronicity (> 12 months) + medial meniscal deficiency	PTS: Borderline/Normal Adj. ΔsATT: High (≥ 7%)	The Meniscal Multiplier: Loss of the posterior wedge and soft-tissue creep create a 'functional PTS increase,' mimicking steep bone.	SRO may be considered on an individualized basis
Type 3: Inherent Soft-Tissue-based (*Hyperlaxity*)	Generalized joint hypermobility (e.g., Beighton score ≥4)	PTS: Variable Baseline sATT: High bilaterally Adj. ΔsATT: Low (≤ 3%)	Symmetric Looseness: Benign, systemic soft-tissue compliance. The anterior shifted set-point is physiological for the patient.	Risk of overtreatment. SRO should be approached cautiously in this phenotype
Double hit A (*synergistic failure*)	Osseous (steep PTS) + acquired soft-tissue-based (meniscal loss/ chronicity)	PTS: ≥ 12° Adj. ΔsATT: Very High	Compounded Risk: A continuous anterior shear vector combined with the complete loss of secondary meniscal containment.	Isolated soft-tissue reconstruction may be at increased risk in this phenotype. SRO may be considered in selected patients to reduce the sagittal shear environment and support restoration of sagittal equilibrium.
Double hit B (*Acute-on-Baseline*)	Inherent soft-tissue-based (hyperlaxity) + acute loss of stabilizers	PTS: Borderline/Normal Baseline sATT: High bilaterally Adj. ΔsATT: High	Lowered Threshold: A highly compliant baseline drastically amplifies sagittal decompensation following sudden structural injury.	Lowered threshold: A constitutionally compliant baseline may amplify sagittal decompensation after acute structural injury.
Double hit C (*compounded risk*)	Osseous (steep PTS) + inherent soft-tissue-based (hyperlaxity)	aPTS: ≥ 12° Baseline sATT: High bilaterally Adj. ΔsATT: High	Compounded Risk: A continuous anterior shear vector is superimposed on an inherently compliant soft-tissue envelope. Because the secondary restraints are systemically hypermobile, they offer minimal resistance to the steep osseous geometry once the primary ligamentous brake is removed.	Compounded risk: A continuous anterior shear vector is superimposed on an inherently compliant soft-tissue envelope. In this setting, constitutional soft-tissue laxity may reduce resistance to PTS-driven anteriorization after loss of the primary ligamentous restraint.
The triple hit (*catastrophic*)	Structural (steep PTS) + acquired soft-tissue-based (meniscal loss/ chronicity) + inherent soft-tissue-based (hyperlaxity)	PTS: ≥ 12° Baseline sATT: High bilaterally Adj. ΔsATT: Extreme	Hostile Biomechanics: Convergence of all variables. Destroys the sagittal set-point. Often presents as atraumatic, early graft failure.	Combined high-risk profile: The coexistence of steep PTS, acquired soft-tissue deficiency, and constitutional hyperlaxity may result in marked sagittal decompensation and a highly unfavourable mechanical environment.

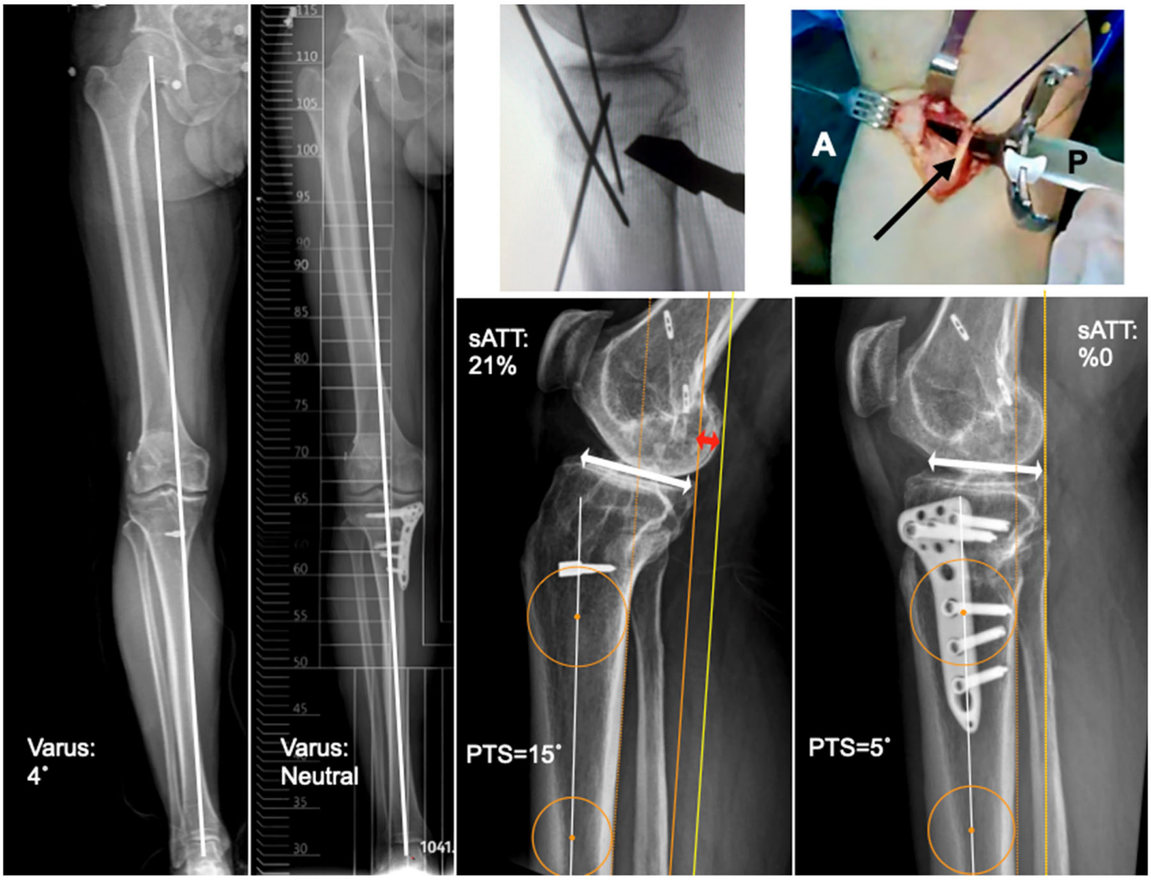

FIGURE 3 Biplanar correction of concurrent coronal and sagittal decompensation using a medial opening wedge high tibial osteotomy (MOW-HTO). Preoperative and post-operative imaging of a patient presenting with a symptomatic varus deformity and concurrent sagittal instability. (Left) Preoperative long-leg standing anteroposterior (AP) radiograph demonstrates a 4° varus mechanical axis deviation, which is successfully corrected to a neutral axis post-operatively. (Bottom Right) The corresponding preoperative monopedal weight-bearing lateral radiograph reveals a highly hostile sagittal profile with a steep posterior tibial slope (PTS) of 15° and a profoundly elevated static anterior tibial translation (sATT) of 21%. Following the MOW-HTO, post-operative imaging confirms the PTS is reduced to 5°, successfully neutralizing the sagittal shear vector and recentering the sATT to a physiological 0%. (Top Right) Intraoperative technique for the biplanar MOW-HTO. The clinical photograph demonstrates the posterior opening of the osteotomy, with the black arrow indicating the medial collateral ligament (MCL) and a spreader placed behind it (A: anterior, P: posterior). The accompanying fluoroscopic image demonstrates anterolaterally placed protective K-wires utilized to allow for controlled PTS reduction while safely protecting the lateral hinge.

execution of these procedures falls outside the scope of this conceptual framework, the ALP system suggests that sagittal corrections should be carefully harmonized with the coronal mechanical axis and the patient's constitutional soft-tissue limits to ensure comprehensive multiplanar stability.

DISCUSSION: MOVING BEYOND RIGID SCORES AND STATIC MORPHOLOGY

The recent literature highlights a critical transition toward individualized indications for SRO, acknowledging that relying on isolated anatomical thresholds is insufficient [21]. However, newly proposed decision-making frameworks remain fundamentally limited by their reliance on static parameters or premature arithmetic scoring [18]. For example, the recently proposed ALPS classification stratifies ACL graft failure risk based on standard deviations of the PTS. While this standardizes purely anatomical risk, it is a strictly morphological approach that fails to account for the functional competence of the secondary soft-tissue envelope under physiological load [17].

In an attempt to integrate these necessary clinical variables, Ollivier et al. introduced the A + STRA score, an algorithm that assigns rigid, weighted point values to concomitant pathologies (e.g., meniscal deficiency, chronological revision status) and limiting factors to dictate surgical intervention [18]. Yet, as compellingly argued by Schuster et al. in their ‘Avalanche Concept’, utilizing rigid scoring systems to dictate ACL revision strategy inherently leads to the oversimplification of pathology [21]. Assigning arbitrary points creates an illusion of precision that suffers from a fundamental lack of evidence in the current literature. The complex, synergistic interrelations between individual biomechanical factors, such as the 'Double Hit' or 'Triple Hit' phenomena, cannot be safely reduced to a definitive yes-or-no arithmetic sum.

The joint-preserving perspective: Proactive versus reactive indications

Most published algorithms, technical descriptions, and clinical series have primarily discussed SRO in the revision ACL setting or in complex cases of recurrent instability, often using elevated PTS, graft failure, tunnel malposition, and associated meniscal deficiency to guide decision-making [15]. Similarly, contemporary scoring systems still tend to emphasize accumulated structural damage or revision-related risk factors before recommending bony correction. For instance, the A + STRA score assigns positive indication points (+2) for a medial meniscus rupture when considering SRO [18]. This reactive logic implies that correcting the osseous PTS is more readily considered after secondary stabilizers have already become functionally compromised.

The ALP system fundamentally rejects this reactive paradigm in favour of a proactive, patient-centric approach. By utilizing sATT to define the specific phenotype driving sagittal decompensation, the algorithm does not arbitrarily divide indications into 'primary' versus 'revision' categories. Instead, it focuses on the biomechanical reality of the anterior tibial shift.

Consider a patient presenting with an acute, primary ACL rupture, an extreme osseous morphology (e.g., PTS ≥ 16° [11]), and completely intact menisci. Under traditional revision-focused algorithms or rigid scoring systems, this patient may not clearly qualify for SRO because the injury is primary and the menisci remain structurally preserved. However, if monopedal weight-bearing radiographs reveal a marked pathological sagittal shift, the joint may already be functionally anteriorized under load. The intact meniscus is now facing a massive, uncompensated continuous shear vector. In this phenotype, the intact meniscus and reconstructed central pivot may be exposed to increased sagittal shear, as elevated PTS has been associated with increased anterior tibial translation, increased ACL/graft forces and altered meniscal loading [1, 10]. Therefore, in selected high-risk osseous anteriorization phenotypes, primary SRO may be considered not only as a salvage procedure, but also as a potential joint-preserving strategy aimed at reducing the sagittal shear environment. Whether this approach prevents subsequent meniscal degeneration or improves long-term joint survival requires prospective clinical validation.

The ALP system resolves this clinical impasse. By classifying patients into distinct sagittal phenotypes (osseous, acquired soft-tissue and inherent soft tissue-based anteriorization), the ALP system aligns with the highly individualized philosophy advocated by Schuster et al. [21], while advancing significantly beyond it by providing a measurable, objective discriminator: monopedal sATT. This framework acknowledges that the sagittal position of the knee under weight-bearing cannot be calculated through arbitrary point totals or estimated through static standard deviations; rather, the severity of sagittal decompensation must be objectively unmasked under physiological load.

Digital implementation: The open-source ALP system calculator

To bridge the gap between complex biomechanical theory and routine clinical application, the ALP system has been operationalized into an open-source, interactive digital calculator. As previously discussed, rigid arithmetic scoring systems inherently oversimplify the synergistic 'Double Hit' or 'Triple Hit' phenomena driving sagittal decompensation. Furthermore, the mathematical process of reverse-engineering osseous asymmetry (ΔPTS) to unmask true soft-tissue incompetence (Adjusted ΔsATT) requires precise calculation that can be cumbersome in a busy outpatient setting.

To resolve this, a web-based clinical tool was developed to instantly process the ALP system. By inputting the raw physiologic weight-bearing radiographic parameters (sATT% and PTS for both the index and contralateral knees) alongside binary clinical modifiers (the presence of chronicity/meniscal deficiency or inherent hyperlaxity), the calculator automates the translation equivalence ratio.

Crucially, the digital framework codifies strict biomechanical safety protocols. It actively prevents the recommendation of an SRO in knees with an index PTS of <12° to avoid potential overtreatment. Utilizing the adjusted parameters, the tool classifies the specific pathomechanical phenotype (e.g., Osseous, Acquired, Inherent soft-tissue based, or combined synergistic 'Hits') and outputs a clear indication of strength. Furthermore, the current interface evaluates meniscal deficiency as a broad parameter rather than distinguishing between specific tear patterns. Although the posterior portion of the medial meniscus is of primary interest regarding its restraint on ATT, there is currently insufficient quantitative evidence to assign distinct algorithmic weights to specific meniscal injuries. The ALP system Calculator is hosted on an open-source repository to ensure universal accessibility (as of April 2026), facilitate ongoing peer review, and encourage

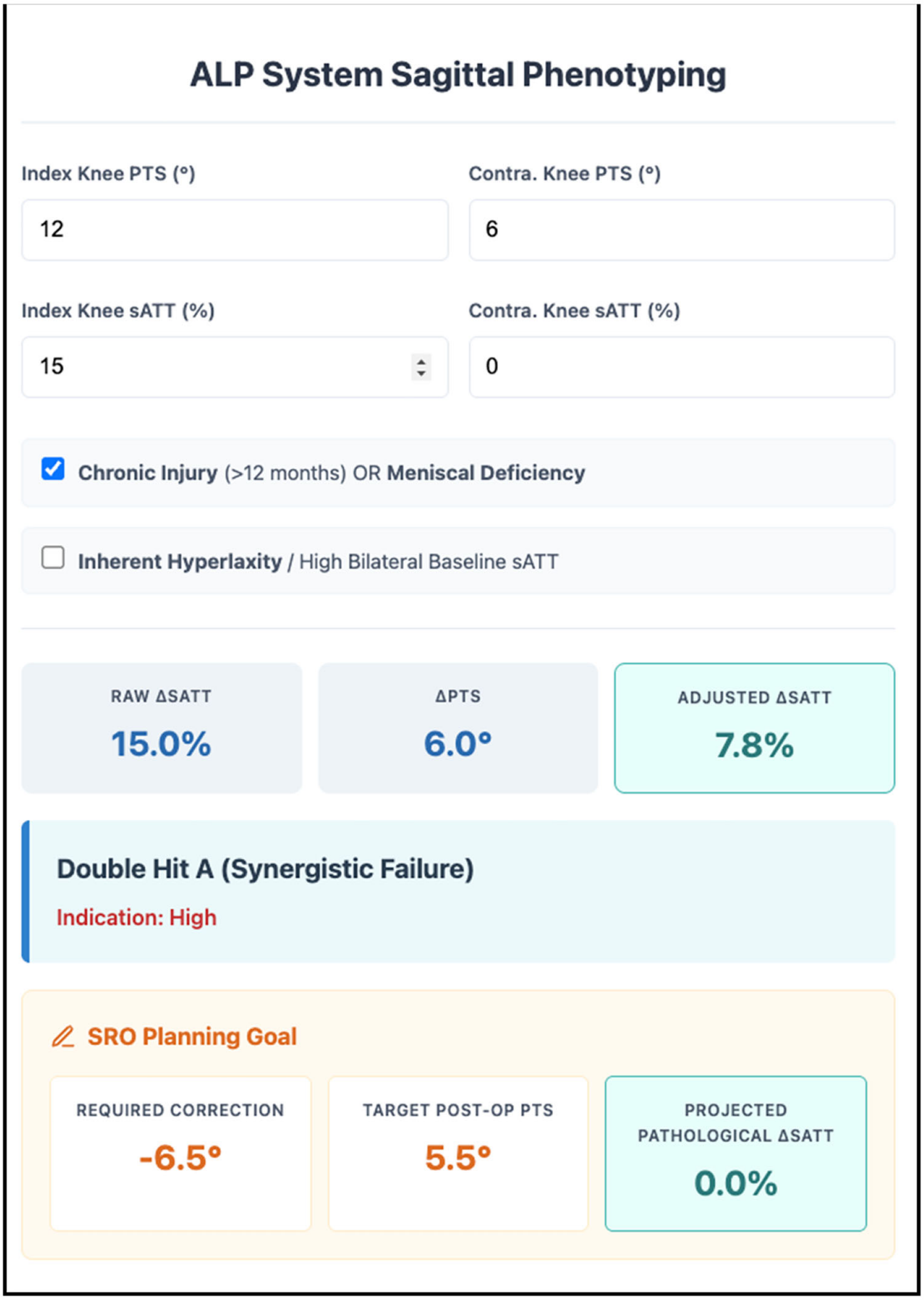

FIGURE 4 The assessment-led personalization (ALP) system digital calculator interface. The open-source web application automates the diagnosis of sagittal knee decompensation. The interface is divided into functional zones: (Top) The clinical input module for strictly acquired monopedal weight-bearing radiographic data (PTS and sATT%) and key clinical modifiers (chronicity and inherent hyperlaxity). (Middle) The biomechanical output, which calculates the raw sagittal shift, factors out the osseous asymmetry (ΔPTS), and isolates the true soft-tissue decompensation (adjusted ΔsATT). (Bottom) The algorithmic output classifying the specific patient phenotype alongside the corresponding indication strength for a slope-reducing osteotomy (SRO), integrating built-in safety overrides for parameters that contraindicate osseous correction (e.g., Index PTS < 12°). PTS, posterior tibial slope; ΔsATT%, side-to-side difference in normalized percentage static anterior tibial translation.

independent prospective clinical validation. As novel biomechanical data emerges, the tool will be regularly updated to refine cut-off values, algorithmic parameters, and potentially incorporate these specific meniscal variables. The tool can be accessed directly at: https://alpsystem.github.io/alp-system-calculator/alp-calculatorWgoal.html (Figure 4), or by scanning the associated QR code (Figure 5).

Clinical Use Disclosure: This calculator serves as an explanatory computational model designed to illustrate the biomechanical approach described in this article using currently available data. It does not

FIGURE 5 Quick response code providing direct access to the open-source ALP system calculator. ALP, assessment-led personalization.

constitute formal medical advice or a definitive surgical treatment recommendation. The application of these concepts to patient-specific scenarios remains the sole clinical responsibility of the treating surgeon. This tool should be regarded strictly as a simplified educational and conceptual guide.

Limitations and future directions

While the ALP system provides a comprehensive, physiologically grounded framework for categorizing sagittal knee decompensation, several limitations must be acknowledged. First and foremost, the ALP system currently serves as a conceptual and strategic approach for patient phenotyping rather than a fully validated, quantitative scoring system.

A primary limitation is the current absence of definitive, universally accepted cut-off values across several key metrics. While the framework utilizes both absolute sATT and ΔsATT as discriminators, the exact thresholds that dictate surgical intervention versus non-operative management or isolated soft-tissue reconstruction remain to be prospectively validated. Furthermore, the specific effect of generalized joint hypermobility on establishing normative, baseline sATT values is not yet fully quantified in the literature. Consequently, defining what constitutes a 'pathological' sATT in a patient with a Beighton score ≥4 requires careful side-to-side clinical judgement rather than reliance on a rigid absolute number.

Additionally, the nuanced role of knee hyperextension requires further elucidation. The ALP system recognizes the danger of the 'recurvatum trap'; however, the isolated biomechanical impact of the knee recurvatum component of the Beighton score, distinct from the total systemic hyperlaxity score, is not yet completely understood.

Finally, thresholds regarding osseous geometry are subject to ongoing debate. The framework lacks established, definitive cut-off values for side-to-side PTS asymmetry (ΔPTS) that might independently justify surgical correction. Even the widely cited absolute PTS thresholds utilized in current literature and incorporated into this algorithm (e.g., PTS ≥ 12°) may evolve. As kinematic data and long-term outcomes of SRO continue to emerge, these geometric cut-offs may prove to be dynamic rather than absolute, potentially shifting based on concurrent soft-tissue status. Future multicentre, prospective studies are imperative to establish precise normative values, validate the predictive accuracy of the osseous, acquired soft-tissue, and inherent soft-tissue anteriorization phenotypes, and ultimately define more refined cut-off values necessary to optimize the ALP system.

CONCLUSION

The ALP system represents a proposed paradigm shift in the evaluation of the ACL-deficient knee, moving beyond the limits of passive laxity to quantify weight-bearing sagittal position. By integrating standardized monopedal weight-bearing sATT with PTS, meniscal integrity and hyperlaxity, the ALP system aims to bridge the diagnostic gap created by relying on isolated osseous thresholds. By identifying compounding risk profiles, such as the 'Double' and 'Triple Hit' phenotypes, the framework may help surgeons refine the indications for PTS-reducing osteotomies, neutralize sagittal shear vectors in selected high-risk patients and avoid potential overtreatment of constitutionally lax knees. Ultimately, the ALP system provides a conceptual precision-medicine framework intended to support restoration of weight-bearing sagittal position, protection of the central pivot and improvement of long-term joint preservation, pending prospective clinical validation.

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DATA AVAILABILITY STATEMENT

Available upon request.

ETHICS STATEMENT

The authors have nothing to report.

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